THE FORMATION OF THE FIRST GLOBULAR CLUSTERS IN DWARF GALAXIES BEFORE THE EPOCH OF REIONIZATION

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ABSTRACT

We explore a mechanism for the formation of the first globular clusters, operating during the assembly of dwarf galaxies at high redshifts, $z \gtrsim 10$. The substructure in the dark matter and the corresponding potential wells are responsible for setting the cluster scale of $\sim 10^5 M_\odot$. The second mass scale in the formation problem, the stellar scale of $\sim 1 M_\odot$, is determined in turn by the processes that cool the gas. We address the origin of the first, cluster mass scale by means of three-dimensional numerical simulations of the collapsing dark matter and gaseous components. We find that the gas falls into the deepest dark subhalos, resulting in a system of ~ 5 proto-globular clouds. The incipient globular clusters lose their individual dark halos in the process of violent relaxation, leading to the build-up of the general dark halo around the dwarf galaxy.

Subject headings: cosmology: theory — early universe — galaxies: formation — clusters: globular — stars: formation — hydrodynamics

1. INTRODUCTION

The origin of globular clusters (GCs) is a longstanding challenge in astrophysics, ever since Peebles & Dicke (1968) have tried to link their formation to the conditions in the early universe, briefly after the epoch of recombination (at redshift $z \sim 1000$). Despite considerable progress in our theoretical understanding (e.g., Fall & Rees 1985; Ashman 1990; Kang et al. 1990; Murray & Lin 1992; McLaughlin & Pudritz 1996; Padoan, Jimenez, & Jones 1997; Nakasato, Mori, & Nomoto 2000; Ashman & Zepf 2001; Cen 2001), the fundamental question of why it is that at early cosmological times bound aggregates of $\sim 10^5$ stars were able to form, remains unsolved. Two recent developments, however, have significantly improved the prospects for real progress.

Observations with the *Hubble Space Telescope* have revealed several merging or recently merged systems which contain extremely luminous young stellar aggregates (e.g., Whitmore & Schweizer 1995). These systems have estimated sizes and masses close to those of Galactic GCs. Therefore, in extreme environments like starburst galaxies, GCs might still be able to form in the present-day universe where we can directly probe the formation process. The second recent development is the increase in computational power which enables us to address the complex physics of collapsing and fragmenting gas with high resolution and the addition of the important physical processes. Therefore, the renewed investigation of globular cluster formation is very timely, and holds the promise of understanding star formation on its grandest scale.

It is likely that there are many avenues leading to the formation of GCs (e.g., Ashman & Zepf 1998). In this *Letter*, we explore one of them and ask: *Could the first globular clusters have formed during the initial stages in the hierarchical build-up of cosmic structure?* Within popular variants of the 'cold dark matter' (CDM) model, the first dwarf galaxies of mass $\sim 10^8 M_\odot$ are expected to collapse at $z \gtrsim 10$. Forming GCs in these dwarf systems might provide an answer to the old puzzle of how to simultaneously account for the two characteristic mass scales involved in the problem: the cluster scale of $\sim 10^5 M_\odot$, and the stellar scale of $\sim 1 M_\odot$, respectively. In the context of our model, the cluster scale is set by the substructure in the dark matter (DM) component, providing the potential wells in which the proto-globular clouds are assembled. The second, stellar, mass scale is then determined by the cooling physics of the star forming gas. We here address the origin of the cluster mass scale by performing numerical simulations of the collapsing DM and gas components. The emergence of the stellar mass scale will be investigated in subsequent, higher-resolution work.

The possible connection between GC formation and DM subhalos has previously been explored semi-analytically by Peebles (1984), Rosenblatt, Faber, & Blumenthal (1988), and Côté, West, & Marzke (2001). Following the demonstration that GCs do not have individual dark halos (Moore 1996), this scenario had lost much of its initial appeal. Considering GC formation during the early stages of the CDM bottom-up hierarchy, however, might also provide a way out of this problem. Due to the flatness of the CDM spectrum on the smallest scales, there is a strong 'cross-talk' behavior,i.e., the roughly simultaneous collapse of all scales (e.g., Blumenthal et al. 1984). The incipient GCs, provided they have condensed sufficiently, could therefore lose their individual dark halo in the process of violent relaxation without being disrupted themselves.

2. THE COSMOLOGICAL CONTEXT

We first outline the basic physical reason why small protogalactic systems of mass $\sim 10^8 M_\odot$, collapsing before the epoch of reionization at redshifts $z \gtrsim 7$ (e.g., Gnedin

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2000), provide intriguing sites for the formation of the first globular clusters. Throughout this paper, we assume that structure formation is described by the ΛCDM model, with a density parameter in matter (both DM and gas) of $\Omega_m = 1 - \Omega_\Lambda = 0.3$, and in baryons of $\Omega_{\rm B} = 0.045$. The Hubble constant is $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}})$=0.7, and the power-spectrum normalization is given by $\sigma_8 = 0.9$ on the $8h^{-1}$Mpc scale.

Within a hierarchical cosmogony, the first dwarf galaxies, of mass $\sim 10^8 M_\odot$, are expected to form out of $\sim 3\sigma$ peaks in the random field of primordial density fluctuations. One can estimate the redshift of collapse (or virialization) to be $z_{coll} \simeq 15$. For such a system, the gas acquires a temperature close to the virial temperature of the DM host halo: $T_{vir} \simeq 2000\,{\rm K}h^{2/3}(M/10^8 M_\odot)^{2/3}(1+z_{coll}) \simeq 10^4\,{\rm K}$. Since structure formation is a bottom-up process, at $z > z_{coll}$ less massive DM subhalos with $T_{vir} < 10^4$ K will collapse first, merging to eventually build up the dwarf galaxy. The 3σ peaks considered here are very likely to be incorporated into larger systems later on. The fate of dwarf galaxies deriving from lower σ peaks, however, is less certain. Whereas 2σ peaks are still expected to collapse before reionization, the more typical 1σ peaks would collapse at lower redshift and would therefore not form GCs according to our model. The 2σ peaks could survive as individual entities and thus correspond to Local Group dwarfs like Fornax and Sagittarius which are observed to have a system of GCs.

A convenient way to quantify the merging history of a galaxy is given by the extended Press-Schechter (EPS) formalism (Lacey & Cole 1993). The EPS prescription allows one to compute the average number of progenitor subhalos at redshift z in a unit range of ln$M$ that will have merged at a later time $z_0 = 15$ into a more massive halo of mass $M_0 = 2 \times 10^8 M_\odot$:

$$\frac{{\rm d}N}{{\rm dln}M} = \sqrt{\frac{2}{\pi}} M_0 \sigma_0(M) \frac{D}{S^{3/2}} {\rm exp}\left(-\frac{D^2}{2S}\right) \left|\frac{{\rm d}\sigma_0({\rm M})}{\rm dM}\right| , \tag{1}$$

where $D = \delta_c(D(z)^{-1} - D(z_0)^{-1})$ and $S = \sigma_0^2(M) - \sigma_0^2(M_0)$. Here, $\sigma_0^2(M)$ is the variance of the linear power spectrum at $z = 0$ smoothed with a "top-hat" filter of mass M, $\delta_c = 1.69$ is the usual threshold overdensity for spherical collapse, and $D(z)$ is the growth factor (Carroll, Press, & Turner 1992). In Figure 1, we show the number of subhalos at different redshifts z that end up as part of an M_0 system at z_0. In comparing the mass functions of the DM subhalos after turnaround, $z_{ta} \simeq 24$, with the observed one for old globular clusters (e.g., Harris & Pudritz 1994), one can see that the respective power-law slopes, dN/d$M \propto M^{-1.8}$, agree quite well in the two cases. This fact suggests that the DM subhalos assemble the requisite high-density gas that might subsequently fragment to form the first globular clusters.

The gas can only fall into the DM subhalos if it is allowed to reach temperatures below $\sim 10^4$K. This requirement explains the importance of the dwarf galaxy forming before the epoch of reionization. After reionization, the intergalactic medium (IGM) is pervaded by a general UV background that photoionizes the gas, and heats it to temperatures $\gtrsim 10^4$K (e.g., Barkana & Loeb 2001). Consequently, the gas in collapsing dwarf systems would not 'feel' the presence of the shallow DM potential wells that are the suspected seeds for GC formation.

Recently, Weil & Pudritz (2001) have investigated how the protogalactic systems studied in this *Letter* would merge to form larger systems. They do not, however, address what happens on scales smaller than ~1 kpc, the resolution limit of their simulation. Our work is complementary to this larger scale study, as we focus on the star formation process in the individual halos on sub-kpc scales.

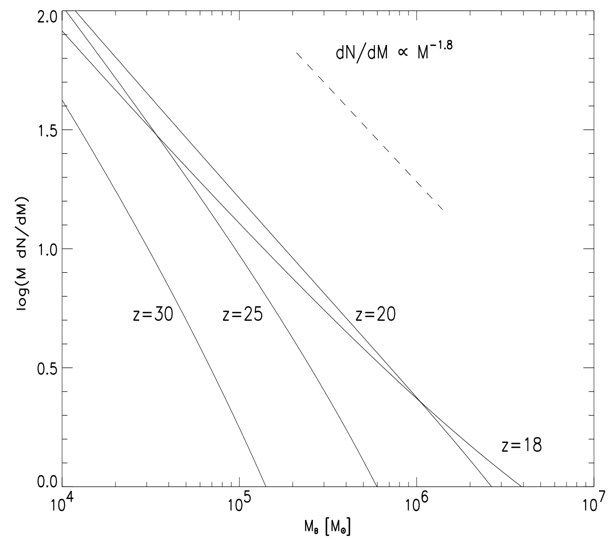

FIG. 1.— Building up the dwarf galaxy. Average number of progenitor halos vs. baryonic mass (in $M_\odot$), formed at z =30, 25, 20, and 18 that, by the later time $z_0 \simeq 15$, will have merged into the dwarf galaxy halo of total mass $M_0 = 2\times10^8 M_\odot$. *Dashed line:* Observed mass function of old globular clusters. It can be seen that, after the redshift of turnaround $z_{ta} \simeq 24$, the mass function of the DM subhalos is very similar to the observed GC one.

3. THE SIMULATIONS

3.1. *Numerical Methodology*

The evolution of the dark matter and gas components is calculated with a version of TREESPH (Hernquist & Katz 1989), combining the smoothed particle hydrodynamics (SPH) method with a tree gravity solver. To follow the thermal evolution of low metallicity gas, we have implemented radiative cooling due to a trace amount of metals at temperatures below $\sim 10^4$K, and due to atomic hydrogen and helium at $T \gtrsim 10^4$K (Bromm et al. 2001b). Prior to reionization there are almost no ionizing photons, and we consequently ignore heating due to photo-ionization.

We have devised an algorithm to merge SPH particles in high-density regions in order to overcome the otherwise prohibitive time-step limitation, as enforced by the Courant stability criterion. To follow the simulation for a few dynamical times, we allow SPH particles to merge into more massive ones, provided they exceed a predetermined density threshold, $n_{th} \simeq 10^3$ cm^{-3}. More details of the code are given in Bromm, Coppi, & Larson (2001a).

Our simulation is initialized at $z_i = 100$, by performing the following steps. The collisionless DM particles are placed on a cubical Cartesian grid, and are then perturbed by applying the Zeldovich approximation (see Bromm et al. 2001a). The power-law index is set to $n = -2.5$ which approximately describes the spectral behavior on the scale of dwarf galaxies. Particles within a (proper) radius of

$R_i = 950$ pc are selected for the simulation. The resulting number of DM particles is here $N_{\rm DM} = 17074$. Finally, the particles are set into rigid rotation and are endowed with a uniform Hubble expansion.

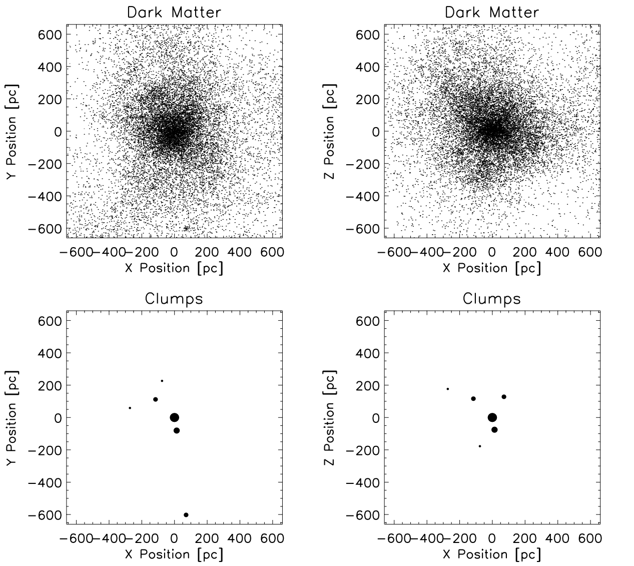

FIG. 2.— Morphology at $z \simeq 15$. *Top row:* The DM component. *Bottom row:* Distribution of clumps with dot size indicating clump mass. *Left panels:* Face-on view. *Right panels:* Edge-on view. The box size is 1.3 kpc. The DM has undergone violent relaxation with the concurrent smoothing out of the substructure. A small system of high-density clumps is left behind.

Angular momentum is added by assuming a spin-parameter $\lambda = 0.05$. The collisional SPH particles ($N_{\rm SPH} = 32768$) are randomly placed to approximate a uniform initial density, and are endowed with the same Hubble expansion and rigid rotation as the DM ones.

We assume that the gas is pre-enriched to a level of $Z = 10^{-2}Z_{\odot}$ as the result of previous star formation activity. We have also carried out simulations with $Z = 10^{-3}Z_{\odot}$ and $Z = 0$, but with the same DM realization, to investigate the effect of varying the cooling physics.

3.2. *Results*

At first, the halo is still expanding, to break away from the Hubble flow and to turn around at $z_{ta} \simeq 24$. At this point, the DM has already developed a marked substructure in response to the initially imprinted density fluctuations. The baryons have begun to fall into the deepest DM potential wells. For this to happen, the gas has to be able to cool below $\sim 10^4$K. Therefore, an efficient low-temperature coolant has to be present: either metals at a level of $Z \gtrsim 10^{-3}Z_{\odot}$ (see Bromm et al. 2001b) or molecular hydrogen. We have verified that the DM induced assembly of gas into the subhalos leads to the same result, irrespective of whether the low-temperature cooling is provided by metals, present at a level 10^{-3} or $10^{-2}Z_{\odot}$, or by H_2. The assembly process, however, does not work if cooling is only due to lines of atomic hydrogen. Once the gas cools and contracts to densities in excess of $n_{th} = 10^3$ cm^{-3}, a sink particle is created. Initially, the sink particle has a mass close to the resolution limit of the simulation, $M_{res} \sim 4 \times 10^4 M_{\odot}$. Subsequently, a sink particle grows in mass by accreting surrounding, diffuse gas, and by merging with other sink particles.

In Figure 2, the situation towards the end of the virialization process is shown.

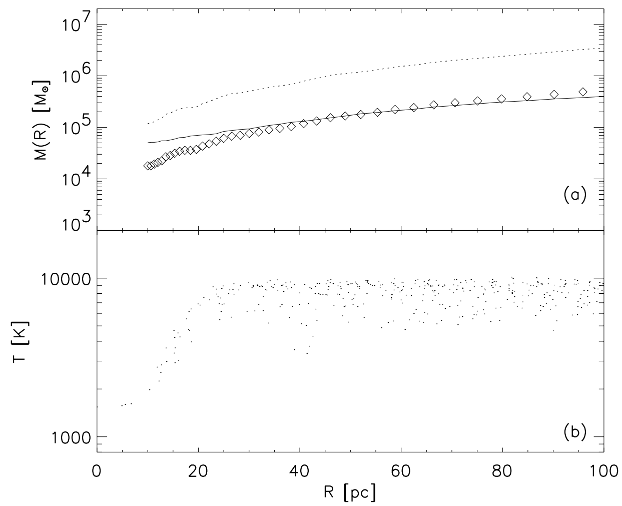

FIG. 3.— Surroundings of the first high-density clump at $z \simeq 24$. (a) Enclosed mass (in $M_{\odot}$) vs. radial distance (in pc) from the density maximum. *Dashed line:* Mass profile of the dark matter. *Solid line:* Mass profile of the baryons. *Diamond-shaped symbols:* Baryonic mass profile scaled from the DM profile with the primordial ratio of gas to DM mass (~ 0.18). (b) Gas temperature (in K) vs. radial distance. It can be seen that the drop in gas temperature at $R \simeq 20$ pc approximately coincides with the baryonic mass profile beginning to deviate from the primordial scaling (see (a)).

The collapse has resulted in the formation of 6 high density clumps, with masses (in units of $10^5 M_{\odot}$): 0.4, 0.5, 2, 3, 13, and 220. The central clump is untypically massive for a GC. This most massive clump, however, differs from the other ones in that it has been assembled over a long period of time ($\Delta t \sim 10^8$yr), and is therefore expected to be chemically inhomogeneous and possibly subject to vigorous negative feedback due to multiple episodes of star formation. The lower mass limit, M_{lower}, is set by the resolution limit of the simulation, $M_{res} \sim 5 \times 10^4 M_{\odot}$. There is, however, also a physical reason for a lower mass cutoff. During the collapse of the halo the Jeans mass obeys the relation: $M_J \gtrsim 10^5 M_{\odot}$ (see Fig. 4), and gas pressure will therefore prevent the baryons from falling into the smallest DM subhalos.

The gaseous clumps appear to have lost their individual DM halos and are embedded in a general, rather smooth DM distribution. This almost complete erasure of the DM substructure might be due to insufficient numerical resolution, as has been recently demonstrated on the scale of large (Milky-Way size) galaxies, as well as of clusters of galaxies (e.g., Moore et al. 1999). The small-scale regime explored here, however, might be special in that the slope of the mass variance becomes almost flat. All scales collapse virtually at the same time, and the individual DM subhalos consequently experience exceptionally strong tidal fields. Only in the smallest galaxies, therefore, might the dissipatively condensed gas clumps lose the association with the DM halos that had given birth to them. Future high resolution simulations will test whether this is indeed the case. Our model could provide an explanation for the existence of co-moving groups of GCs in the halos of large galaxies, as claimed by Ashman & Bird (1993) in the case of M31.

In Figure 3, we show the properties of the gas in the vicinity of the first high-density clump. At $r \sim 20$ pc, the gas mass profile begins to deviate from the primordial behavior, $M_{\rm B}(r) = 0.18 M_{\rm DM}(r)$.

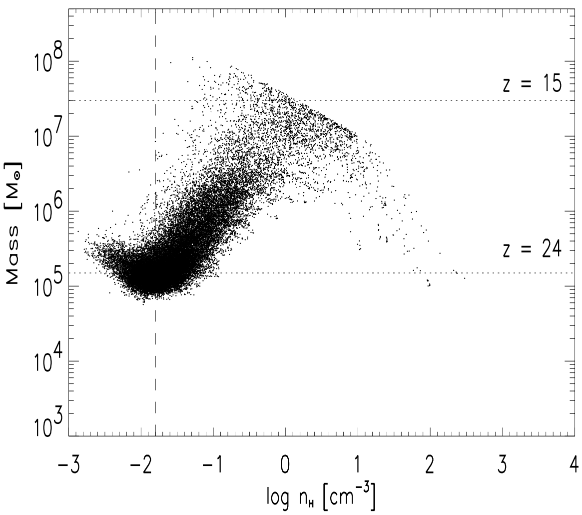

FIG. 4.— The bottom-up assembly of gas in a collapsing dwarf galaxy. Gas mass (in $M_{\odot}$) vs. hydrogen number density (in cm^{-3}). *Small dots:* Jeans mass evaluated for every SPH particle at the moment of turnaround, $z_{ta} \simeq 24$. *Dotted lines:* Baryonic mass of a halo corresponding to a 3σ peak at redshifts $z = 24$, and 15. *Vertical dashed line:* Condition that the free-fall time equals the Hubble time at $z = 15$. Only the particles to the right of this line, comprising $\sim 70\%$ of the total gas mass, have a chance to be incorporated into a high-density clump.

Closer in, at $r \sim 10$ pc, the gas becomes self-gravitating. The DM density in the virialized subhalo is $\rho_{\rm DM} \sim 10^{-21}$g cm^{-3}, corresponding to a gas density of $n \sim 10^2\mathrm{cm}^{-3}$. Since sink particles are created at $n_{th} = 10^3\mathrm{cm}^{-3}$, the high-density clumps physically represent self-gravitating clouds. These clouds are the possible progenitors of globular clusters. Notice the importance of the gas being able to cool below $\sim 10^4$K, in order to fall into the DM potential well (Fig. 3b). A radius of ~ 10 pc constitutes an upper limit to the true size of a GC. The final cluster is expected to be more compact than the simulated clumps. GCs are observed to show a lack of correlation between mass and radius (e.g., Ashman & Zepf 2001). Any mass-radius relation in our simulation would be a numerical artefact, since sink particles (clumps) are created at a fixed density. Determining the precise nature of the $M - R$ relation and the true radial extent of the GCs require higher-resolution simulations which we plan to carry out in future work.

In Figure 4, we estimate the mass range of the resulting clumps. We compute the Jeans mass for each gas particle using the total (DM + baryonic) density at a redshift of 24. We also show (horizontal lines) the baryonic mass of a 3σ peak at redshift 24 (turnaround) and 15 (virialization). At first the highest density gas collapses into a $\sim 10^5 M_{\odot}$ halo (see Fig. 3). Subsequently, more massive clumps form, up to the collapse of the dwarf galaxy itself. For gas with $T \gtrsim 10^4$K, characteristic of photoionization-heated gas, the Jeans mass would be $M_J \gtrsim 10^7 M_{\odot}$, hence making it impossible to form any high density clumps in the small DM subhalos. Again, this shows that the GC formation mechanism proposed in this *Letter* can only operate at redshifts beyond reionization.

4. SUMMARY AND CONCLUSIONS

The collapse and virialization of the dwarf galaxy results in the formation of six high density clumps, with masses $10^5 \lesssim M \lesssim 10^7 M_{\odot}$, and typical radii ~ 10 pc. The resulting clump masses are determined by the mass spectrum of the DM substructure, provided the gas can cool sufficiently to fall into the shallow DM potential wells. This is the case in the presence of an efficient coolant that is able to operate at $T \lesssim 10^4$K, but is prohibited after the universe underwent reionization. In our simulations, the highly condensed gas clouds have lost their individual DM subhalos, which we tentatively ascribe to the exceptionally strong tidal forces acting during the relaxation of a dwarf galaxy at high redshift.

The expected metallicity distribution of clusters formed in this way needs further investigation. We note that the time between turnaround and virialization, which marks the interval over which GCs are assembled in our model, is around 10^8yr, and thus in principle there is time for the nucleosynthetic products from one cluster to reach the gas destined to form another cluster. It is currently unclear whether this could explain the significant spread in metallicity observed among the clusters in the Fornax and Sagittarius dwarfs (e.g., Buonanno et al. 1998), or whether these data require that some of the clusters form at significantly later epochs.

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